Predictability of Speech-In-Noise Performance from Real Ear Measures of Directional Hearing Aids

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Objective: **Inability to understand speech in noise has been cited repeatedly as the principal complaint of hearing aid users. While data exist documenting the benefit provided by hearing aids with directional microphones when listening to speech in noise, little work has been done to develop a standard clinical protocol for fitting these hearing aids. Our goal was to evaluate a clinical measure of the acoustic directivity of a directional hearing aid, including its association with a test of speech perception in noise.**

Design: **The performance of two commercially available directional behind-the-ear (BTE) hearing aids was evaluated using the Hearing in Noise Test (HINT) and the Real Ear Aided Response (REAR) on 24 adult participants with symmetric, mild to moderately severe, sensorineural hearing loss. The HINT was conducted with the speech signal presented from 0° and the noise from 180° and either 135° or 225° degrees, depending on the ear tested. REAR was measured at the above three angles using swept pure tones, and these measures were used to compute in situ directivity for each subject and hearing aid.**

Conclusions: **Directional benefit for the HINT was greatest when noise was presented from the azimuth of the published polar diagram null of a given hearing aid in its directional mode (180 or 135/225°). The only significant correlation between HINT and REAR results, however, was found when the noise source was at 180°. These results confirm the validity of using real ear measures as a way to assess directionality in situ, but also indicate the complexity of predicting perceptual benefit from them. These data suggest that factors beyond acoustic directionality may contribute to improvement in speech perception in noise when such improvements are found.**

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Inability to understand speech in noise remains one of the most common complaints among hearing aid wearers today (Kochkin, 1996; Ricketts & Dhar, 1999; Schum, 2000; Smriga, 2000; Voll, 2000). Provision of effective amplification in the presence of background noise is indeed one of the greatest challenges to researchers and audiologists (Preves, 2000). Although normal-hearing individuals experience difficulty in speech perception in the presence of background noise, many hearing-impaired listeners often need an even greater signal-to-noise ratio (SNR) to successfully perceive speech in noise (Killion, 1997).

Directional microphones, which have been implemented in hearing aids since the early 1970s (Agnew & Block, 1997; Lentz, 1972; Valente, Fabry, & Potts, 1995), appear to provide the most effective solution to the problem of reduced speech perception in noise. Recent revival of interest in directional microphones has resulted in increased research focus and commercial implementation of this technology (Christensen, 2000; Preves, Sammeth, & Wynne, 1999; Valente et al., 1995). The rekindled interest in directional microphones is based on three factors: increased directivity available today [as measured by the Directivity Index (DI)]; the ability to implement directional microphones in in-the-ear and in-the-canal style hearing aids; and the ability of the wearer to switch between omni and directional microphones (Christensen, 2000). Voll (2000) provides a detailed discussion on design aspects of directional microphones and the differences between earlier and present-day implementations.

Several researchers have recently documented the improvement in SNR due to directional microphones (Agnew, 1997; Christensen, 2000; Killion, 1997). Killion (1997) reported that directional microphones can improve SNR by 3 to 5 dB in noisy, reverberant environments, and up to 5 to 10 dB in nonreverberant listening environments. This small increase in SNR may not appear significant. However, a change in SNR as small as 1 dB can result in a 10% increase in speech understanding for meaningful sentences (Venema, 1999), thereby making even minimal improvements in SNR highly desirable.

With the benefits of directional hearing aids established, research focus has shifted to the quantification and prediction of directional benefit in the end user. The directivity of a hearing aid can be quantified using either acoustical or behavioral

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measures. The physical performance of a hearing aid without the influence of the user is determined using acoustical measures. Behavioral measures, on the other hand, quantify the combined performance of the individual user and a particular hearing aid. Examples of acoustical measures include front-to-back ratios (FBRs) and DIs. While a brief description of each of these measures follows, Valente (1998) provides a more detailed tutorial.

The FBR measures the difference in the output of a hearing aid for signals from the front (0° azimuth) in comparison to signals from the back (180° azimuth). It is generally presumed for this measurement (and throughout this paper) that the signal of interest (speech) is presented at the front of the listener while the noise source is located to the rear. Therefore, FBR indicates the effectiveness of the hearing aid in improving SNR by reducing the noise coming from behind. Unlike FBR, which only takes into consideration 0° and 180°, DI is the ratio of the hearing aid's output for a sound source at 0° to the combined output of sound sources at all other angles (in the same horizontal plane).

The DI of a hearing aid is typically depicted through illustrations known as polar plots. Omnidirectional microphones are theoretically designed not to give preference to sounds coming from any one direction. Thus, omnidirectional microphones have a DI of 0 dB and their polar plot is circular. It should be noted, however, that the polar plot is distorted when the microphone is mounted on a hearing aid and the hearing aid is fitted on an actual patient (Dillon, 2001; Fortune, 1997). This is due to the directivity provided by the human head and outer ear, primarily through sound shadow.

Directional microphones have a variety of polar plot configurations resulting in a corresponding variety of DI values. These values are dependent on how much the sound is being amplified or suppressed from every direction. Generic polar patterns for production hearing aids are readily available from manufacturers, and Ricketts and Mueller (1999) or Christensen (2000) offer an extensive treatment of technical aspects of polar plots. Even though DI measures are very thorough and informative, at least in a two dimensional sound field, they can be difficult to measure in an average clinical setting. FBRs, however, can easily be measured using standard hearing aid test equipment.

Real-ear measurement, the de facto clinical standard for the evaluation of in situ hearing aid performance, provides the clinician with several advantages over corresponding behavioral measures, such as speed, objectivity, and ease of administration. Real-ear measurement techniques can easily be adapted to evaluate the directionality of hearing aids without any modification of either the hardware or software of the standard equipment. A quick measure of FBR can be obtained by measuring the difference in REARs with the signal source at 0° and 180° (Mueller, Hawkins, & Northern, 1992), thereby providing a rapid yet reliable acoustic measure of directionality.

The ultimate goal in measuring benefit from directional hearing aids is to estimate the amount of improvement that a user would experience in day to day "real world" listening environments. Researchers are beginning to focus on the development of clinical tests that could accurately predict real world benefit from directional hearing aids. The HINT is one such test that has been proposed to predict real world directional benefit (Ricketts & Mueller, 2000). The HINT is a pre-recorded sentence test designed to measure speech-recognition performance in the presence of speech-shaped background noise through the adaptive measurement of speech-recognition threshold (or threshold SNR). Threshold SNR is established based on the signal level required for 50% performance.

Although it is now accepted that the HINT offers a valid measure of directional benefit, some inherent drawbacks pertaining to its regular administration as a clinical tool need to be addressed. Apart from the necessity for a two-speaker set up, the HINT demands specific calibration of the output. Two 20-sentence blocks have to be administered to be able to reliably compare omnidirectional and directional results. Even then, as a behavioral measure, reliability is likely to be less than that of acoustical measures of directivity. Obtaining threshold SNR requires manual calculations for each test block. (It should be noted, however, that this operation can be automated by using a computer-controlled audiometer along with commercially available custom software.) The above mentioned constraints notwithstanding, the HINT remains one of the most viable and practical clinical tests of directional benefit.

Recently, several researchers have published encouraging results demonstrating benefit from new generation directional hearing aids (Ricketts & Dhar, 1999; Valente et al., 1995). Several commercially available hearing aid models have been compared in some of these studies. Although directional benefit from two commercially available hearing aids was measured in the study reported here, the goal of this study was not to simply document their effectiveness or compare their performance. The overall aim of this study was to evaluate the possibility of predicting behavioral directional benefit (as measured using the HINT) using a fast, simple, acoustical tool such as REAR. In the process of this evaluation, we also hoped to identify relevant fac-

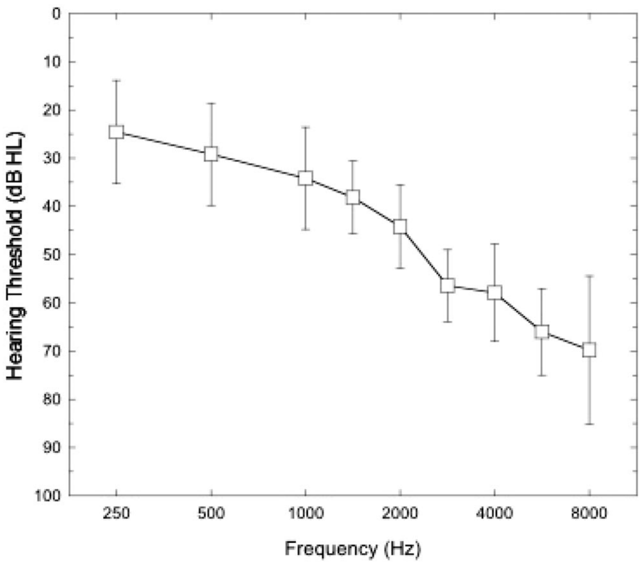

Figure 1. Mean audiometric thresholds (N = 24). Error bars represent one standard deviation.

tors contributing to directional benefit in hearing aid users. The clinician has to make a decision to fit a directional hearing aid based on manufacturer-supplied information, such as DI and polar plots. Most or all of this information is limited to the acoustic directivity of a hearing aid but the clinician (and patient) is finally interested in speech perception benefits that the hearing aid might provide in background noise. Thus, the question remains: Does acoustic advantage in isolation translate directly to greater benefit in speech perception in noise? If there is not a one-to-one correspondence between acoustic advantage and better speech perception in noise, what other factors does the clinician need to consider before choosing directional amplification in general or a product in particular? Thus, our goal was to first determine the predictability of speech perception in noise from acoustic measures and then to begin probing for "extra-acoustic" variables that might contribute to the overall performance of the hearing aid user.

Methods

Subjects included 24 adult listeners (10 male and 14 female) between the ages of 30 and 89 yr (mean, 69.9 yr) with symmetric, mild to moderately severe, sensorineural hearing loss. Mean air conduction pure tone thresholds, along with error bars representing ± 1 standard deviation, appear in Figure 1. All subjects were recruited from the patient pool at the Indiana University Hearing Clinic. None of the subjects participating in this study had any prior experience using directional hearing aids. However, 7 of the 24 subjects had previous experience using hearing aids, with the amount of prior experience ranging from 2 to 16 yr. Although every subject had undergone comprehensive diagnostic testing previously, pure tone thresholds were re-evaluated prior to the experimental session. No significant air-bone gap (≥15 dB) was present in any subject at any test frequency (250–4000 Hz).

Two hearing aids were examined in omnidirectional and directional modes. Aided testing was conducted using the following monaurally fit BTE hearing aids: (1) Oticon DigiFocus Compact Direct; and (2) Phonak Piconet P2 AZ. The hearing aids were programmed using modules, supplied by the manufacturer, that were run through NOAH software on an Intel-based personal computer. Pure tone thresholds were input into the software, and gain and compression parameters were calculated according to manufacturer-suggested algorithms. The authors were aware of the availability of newer products from each of these manufacturers, claiming better performance in noise. However, the choice of hearing aid models was largely irrelevant to the overall goals of the study. Note that noise reduction signal processing algorithms are not employed in either of these hearing aids.

Super compression with adaptive release time was selected for all Phonak fittings, as suggested by the manufacturer. This instrument was switched between omnidirectional and AudioZoom directional modes using the toggle (M-T-O) switch on the body of the instrument. The Oticon DigiFocus aid was programmed using the prescribed Otiset fitting strategy and was switched between directional modes using the toggle switch on the body of the instrument also. The frequency response of the hearing aid was not altered in the directional mode manually. Thus, equalization of response or lack thereof was programmed in the directional mode as per the manufacturers' default specifications.

Both hearing instruments used in this study use a two-microphone design, i.e., two omni-directional microphones are used in combination in the directional setting. The specific polar patterns for the instruments used in this study were not measured, but generic polar patterns for these models are readily available from the manufacturers. In brief, the polar patterns for both instruments are generally cardioid in shape, with a critical difference in the location of the null. The null appears at approximately 180° for the Phonak instrument, while it appears at 135/225° for the Oticon instrument, depending on whether the hearing aid is worn in the left or right ear. The frequency responses of the hearing aids as measured for one subject are presented in Figure 2. Examination of the response of

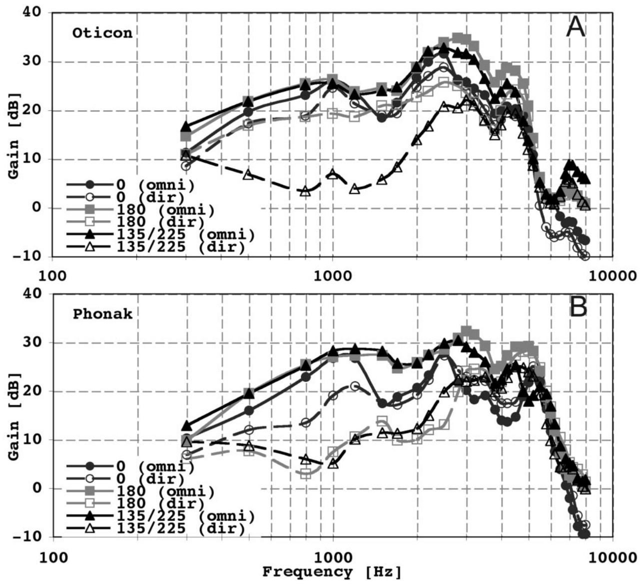

Figure 2. Results of REAR measurements for one subject using the hearing instruments used in the study. The hearing aid is identified in the individual panels (Oticon: Panel A; Phonak: Panel B) that display the frequency response of the hearing aids for omnidirectional and directional modes from different azimuths. Note the varying degrees of directionality from different azimuths as well as the varying amounts of frequency equalization employed. (dir = directional mode; omni = omnidirectional mode)

each hearing aid in the directional and omnidirectional modes for 0° azimuth reveals an unequalized response for the Phonak instrument. The frequency response of the Oticon instrument is equalized between the directional and omnidirectional modes. Comparisons of these responses at the other azimuths, on the other hand, reveals directional effects for each instrument. A calibration setting was programmed into NOAH, and the hearing aids were tested for these settings at the beginning of every week for the duration of the experiments. This involved electroacoustic evaluation of the instruments using American National Standards Institute (ANSI) (1996) standards on a hearing aid analyzer and ensured consistency of hearing aid functioning across subjects. The hearing aids were also evaluated electracoustically using the ANSI (1996) protocol after they were programmed for each subject. The hearing aids were coupled to the subjects' ears via a custom-made, Lucite, skeleton earmold with a parallel 1-mm vent. All tests were conducted monaurally and the non-test ear was plugged using a Classic EAR foam earplug.

Both the HINT and real-ear measurements were conducted in a sound-treated, double-walled audiometric booth. The HINT was administered via two calibrated Optimus Pro AV speakers. These speakers were set at a fixed height of 36 inches from the ground, and placed 18 inches from the tragal notch of the subject's test ear for all azimuths. The signal and competition were presented through the speakers at 0° and 180°, respectively, under one of two possible test configurations. In an additional test configuration, the signal azimuth remained the same (0°) but the noise azimuth was moved to an angle 45° toward the test ear. Thus, the noise source was placed at 135° and 225° for the right and left ears, respectively. This was done to accommodate the nulls in published polar-plot patterns of the hearing aids used in these experiments. Tests were conducted using 20-sentence blocks for each directional mode (omnidirectional, directional) for each hearing aid (Oticon, Phonak) and each test configuration (0°/180°, 0°/135° or 225°). A total of eight test conditions were used for the HINT that made use of 160 of the 250 sentences available. No sentences were repeated during testing.

Real-ear aided responses were also measured using the same test configurations. All measurements were made using swept pure tones controlled by a Fonix FP6500 hearing aid analyzer. The signals were presented through two calibrated Realistic Minimus 3.5 speakers. The probe tube was placed 25 mm into the ear canal from the tragal notch with the reference microphone fixed to the subjects' head with a Velcro strap. Unaided real ear responses were recorded at 0°, 180°, and 135/225° (θ[135/225]) for a total of three unaided measures. While the unaided measures were not used directly in this study, they were obtained for use in subsequent Speech Intelligibility Index (SII) calculations. Aided real ear measures were also recorded for both hearing aids at the same angles in omni- and directional modes. Thus, six measurements (3 azimuths $\times$ 2 directional modes) were obtained for each of these hearing aids resulting in 12 measurements for each subject. These, with the initial 3 unaided measures, made for a total of 15 different real-ear measures for each subject.

The noise level was fixed at 65 dBA for the HINT, while the level of the speech signal was varied based on the subjects' responses. A swept pure tone at 60 dB SPL was used for the real ear measures. The responses of the hearing aids for composite and swept pure tone stimuli were compared in a Zwislocki coupler mounted on a KEMAR and the difference in responses to these two stimulus types was found to be negligible. The reader is directed to a publication from Frye Electronics for their recommended protocol for measuring directional characteristics of a hearing aid.* Frye Electronics recom-

*(http://www.frye.com/library/acrobat/directionalha.pdf)

mends turning the reference microphone off during these measurements to eliminate any effects of the reference microphone facing different directions during measurements from the front and back. However, these differences when present are expected to be negligible and should not have critically influenced the results of this study. The order of administration for directional mode, hearing aid, azimuth and HINT versus real-ear was counterbalanced.

The procedures followed in the study were approved by the Institutional Review Board at Indiana University and all subjects provided informed consent. Subjects were paid $25.00 for their participation.

RESULTS

The basic aim of this study was to examine the predictability of directional benefit (as measured in the sound field by the HINT) using real-ear measures. We measured the performance of two commercially available BTE hearing aids for the behavioral (HINT) and acoustic (REAR) measures of directivity in 24 subjects. The results of the HINT and real-ear measures are reported independently first to facilitate comparison with previous research, as well as to provide the reader with the raw data on which the subsequent correlational analyses were based.

HINT Results

Mean HINT SNR values for each hearing aid are reported in Figures 3 and 4 for omnidirectional and directional modes, respectively. HINT SNR values for both directional modes are depicted in traditional fashion, where better performance is expressed as lower (more negative) SNR. This SNR is calculated as the decibel difference between the threshold speech level and the 65 dBA background noise level.

For the omnidirectional mode (Figure 3), performance was better for both hearing aids when the noise source was at 180° as compared with θ[135/225]. Differences in performance among the hearing aids were examined with a repeated measures analysis of variance. Significant differences between hearing aids were not observed for either angle in omnidirectional performance. The results of a similar analysis for the directional mode (Fig. 4) did yield significant differences ($p < 0.01$) among the hearing aids for the 180° azimuth only, with the Phonak instrument performing significantly better than the Oticon instrument. Performance differences between hearing aids associated with noise azimuth are not as consistent as were observed in Figure 3. The Oticon instrument performed better when the noise source was at θ[135/225], while the Phonak instrument performed better with the noise at 180°. This was not unexpected and is reflective of the differences between the published polar patterns of the hearing instruments.

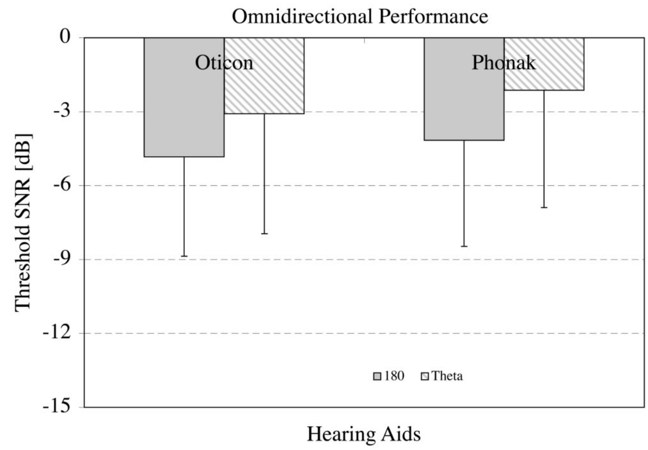

Figure 3. Performance in the omnidirectional mode for two speaker configuration. The shaded and hatched bars represent measurements made with a noise source at 180° and at either 135° or 225° degrees, respectively. This off-angle is referred to in general as θ[135/225]. The signal was presented from a speaker at 0° in both cases. Results are displayed in the conventional format for HINT scores where a more negative score signifies better performance. The error bars depict ± 1 standard deviation.

Directional benefit, calculated as the difference between omnidirectional and directional performance for the hearing aids, is displayed in Figure 5. The format of the figure is similar to that of Figures 3 and 4. The depiction of greater benefit by positive numbers is the primary difference between this and the previous figures. Differences between the instruments in SNR benefit were significant ($p < 0.01$) when the noise was presented at 180° only, with the

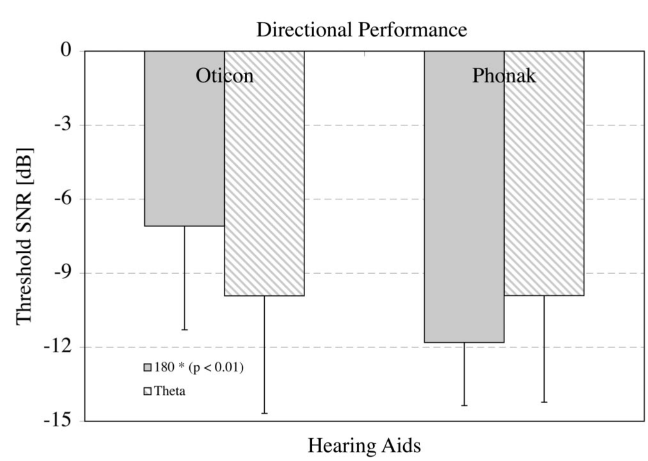

Figure 4. Performance in directional mode for two speaker configurations. The format of the figure is similar to Figure 3.

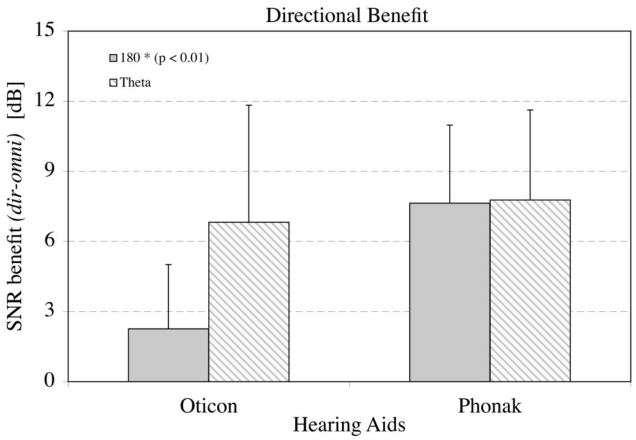

Figure 5. Directional benefit as calculated by the difference between directional and omnidirectional performance. Error bars depict ± 1 standard deviation.

Phonak instrument providing significantly greater benefit as compared with the Oticon instrument.

Real-Ear Results

Real-ear measures were obtained from all subjects with signal sources at 0°, 180°, and θ[135/225] in both omnidirectional and directional modes, providing six REAR measures for each subject and hearing-aid combination. Representative REAR results from one subject were displayed previously in Figure 2. These results point towards the nature of directivity of these hearing aids. Note that directivity is higher for the noise source at θ[135/225] for the Oticon hearing aid. The amount of directivity for the Phonak hearing aid appears to be similar for noise sources at both 180° and θ[135/225]. The degree of response equalization utilized by each of these circuits is also evident in Figure 2, as noted previously.

REAR values obtained at frequencies between 200 and 6000 Hz using a swept pure tone at 60 dB SPL were averaged to yield a single value for each condition. These values are represented as $R^{\phi}_{omni,dir}$, where ϕ is the angle of signal presentation and *omni,dir* represent omnidirectional and directional modes, respectively. The REAR measures were used to compute in situ acoustic directivity for each subject from a given hearing aid. We define acoustic directivity ($\mathscr{AD}^{\varphi}$), where φ is the angle of incidence of the noise, as follows:

$$\mathscr{AD}^{\varphi} = FBR^{\varphi}_{dir} - FBR^{\varphi}_{omni}\,, \qquad (1)$$

where $FBR^{\varphi}_{omni,dir} = R^{0}_{omni,dir} - R^{\varphi}_{omni,dir}$. Note that φ is the azimuth of noise (180° or θ[135/225]) in a communication situation as opposed to the signal or speech, which was always at 0° azimuth. Also note that the order of the terms in the right hand side of Equation 1, although perhaps counter-intuitive, was chosen to yield a positive value for acoustic directivity for directional hearing aids. Equation 1 can be expanded to demonstrate the computation of $\mathscr{AD}^{\varphi}$ from the results of REAR measurements by replacing $FBR^{\varphi}_{omni,dir}$ with its constituent terms.

$$\mathscr{AD}^{\varphi} = (R^{0}_{dir} - R^{\varphi}_{dir}) - (R^{0}_{omni} - R^{\varphi}_{omni}) \qquad (2)$$

As directional microphones are built with the assumption that the signal of interest is always at 0°, the sensitivity of a directional hearing aid is not expected to change (theoretically, at least) for signals from 0° azimuth between omni-directional and directional modes (*i.e.*, $R^{0}_{omni} = R^{0}_{dir}$). If this presumption is considered valid, a simpler (for measurement purposes) variant of $\mathscr{AD}^{\varphi}$, denoted here as $\mathscr{AD}^{\varphi}_{s}$, can be computed as follows:

$$\mathscr{AD}^{\varphi}_{s} = R^{\varphi}_{omni} - R^{\varphi}_{dir} \qquad (3)$$

The measurement of $\mathscr{AD}^{\varphi}_{s}$ is considerably simpler than that of $\mathscr{AD}^{\varphi}$ since this can be achieved without having to change the position of either the subject or the loudspeaker. These issues are discussed in further detail in the next section.

The equivalence between $\mathscr{AD}^{\varphi}_{s}$ and $\mathscr{AD}^{\varphi}$ is dependent on the invariance of the hearing aid's sensitivity to signals from 0° in omnidirectional and directional modes. However, it is well known that this assumption is violated in most, if not all, commercially available hearing aids. Often, for example, the hearing aid's frequency-gain characteristics (*FC*) change as the hearing aid is switched between omnidirectional and directional modes (as demonstrated previously for these hearing aids in Figure 2). This difference, *FC*, is essentially the difference in a hearing aid's response to signals from 0° azimuth in omnidirectional and directional modes. As demonstrated below, *FC* can also be computed as the difference between $\mathscr{AD}^{\varphi}_{s}$ and $\mathscr{AD}^{\varphi}$.

$$\begin{aligned} FC &= \mathscr{AD}^{\varphi}_{s} - \mathscr{AD}^{\varphi} \\ &= (R^{\varphi}_{omni} - R^{\varphi}_{dir}) - \{(R^{0}_{dir} - R^{\varphi}_{dir}) - (R^{0}_{omni} - R^{\varphi}_{omni})\} \\ &= R^{0}_{omni} - R^{0}_{dir} \end{aligned} \qquad (4)$$

Results of a multi-factorial analysis of variance with repeated measures for $\mathscr{AD}^{\varphi}$, $\mathscr{AD}^{\varphi}_{s}$, and *FC* are presented below with hearing aid as the independent variable in each case. The mean values for $\mathscr{AD}$ for both 180° and θ[135/225] are presented in Figure 6. There were no significant differences in the acoustic directivity measured between the hearing aids when the noise source was at θ[135/225]. However, a significant difference in $\mathscr{AD}^{\varphi}$ was observed for noise at 180°, with the Phonak instrument providing

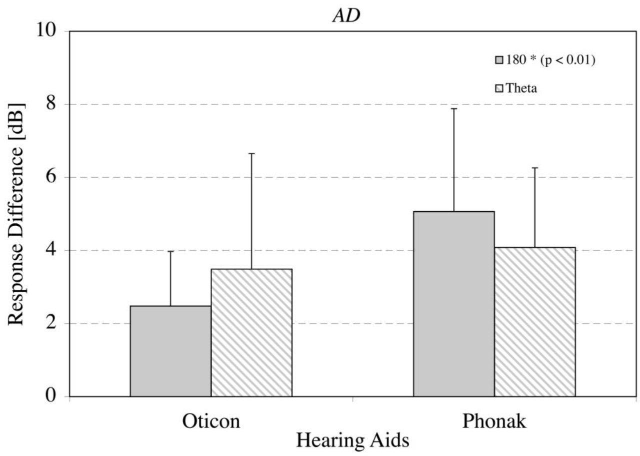

Figure 6. Mean acoustic directivity ($\mathcal{AD}^{\varphi}$) as measured using real-ear for the two hearing aids tested. The format of the figure is similar to Figure 5. The error bars represent ± 1 standard deviation.

significantly more directivity than the Oticon instrument.

Equation 3 provides an alternate and more convenient method of estimating acoustic directivity provided by hearing aids. Mean values for $\mathcal{AD}_s^{\varphi}$ for noise sources at 180° and θ[135/225] are presented in Figure 7. The results are similar to those for $\mathcal{AD}^{\varphi}$ displayed previously in Figure 6. The mean $\mathcal{AD}_s^{\varphi}$ values for both noise angles and both hearing aids, however, are higher than the corresponding $\mathcal{AD}^{\varphi}$ values. Additionally, performance of the Oticon hearing instrument is no longer significantly different from that of the Phonak instrument.

The difference between $\mathcal{AD}_s^{\varphi}$ and $\mathcal{AD}^{\varphi}$ can be computed as demonstrated in Equation 4. It can be argued that this difference (*FC*) is independent of the directivity of the hearing aid and is induced due

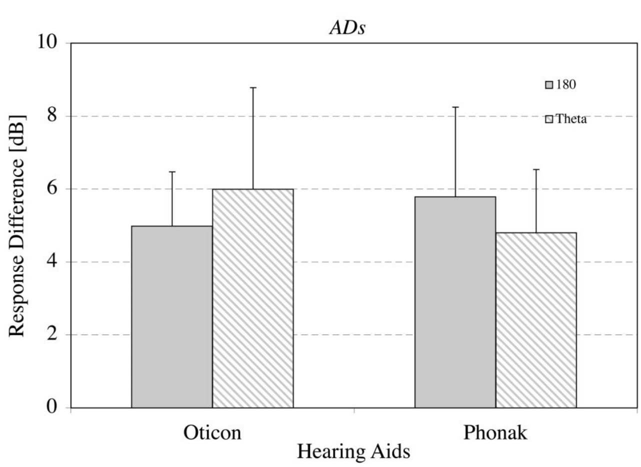

Figure 7. Mean acoustic directivity ($\mathcal{AD}_s^{\varphi}$) as measured using Equation 3 for the hearing aids. The error bars represent ± 1 standard deviation.

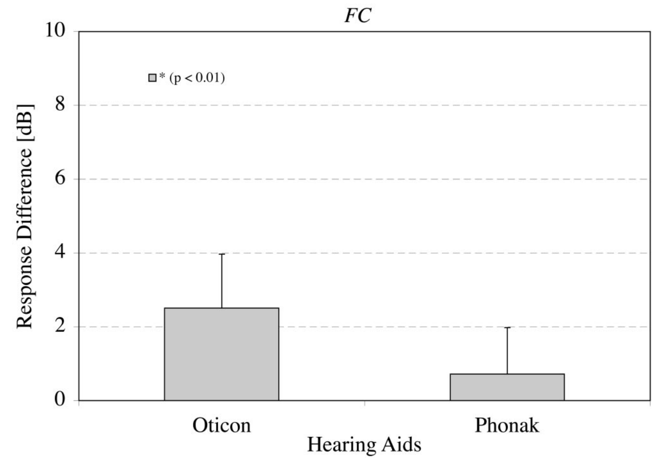

Figure 8. Difference between REAR values for omnidirectional and directional modes (*FC*) for signals at 0° indicating a change in frequency response of hearing aids independent of directivity. The error bars represent ± 1 standard deviation.

to other changes in the instrument's response characteristics when switched from the omni-directional to the directional mode. The source of *FC* and its implications on hearing aid performance are discussed in detail in the next section. The mean values for *FC* for the three hearing aids are displayed in Figure 8. *FC* was found to be significantly higher ($p < 0.01$) for the Oticon instrument.

Predictability

The overall aim of this study was to examine the predictability of behaviorally-measured directional benefit as measured using the HINT, using an efficient acoustic measure such as real-ear measurement. While we have presented the group data for each of the tests involved thus far, here we present the correlation between the individual HINT and real-ear results. Recall that we computed acoustic directivity from real-ear measures using two related, but different, techniques ($\mathcal{AD}^{\varphi}$ and $\mathcal{AD}_s^{\varphi}$. Here, we present the results of correlational analyses between each of these variables and directional benefit as measured using the HINT.

Pearson's correlation coefficients between directional benefit, as measured by HINT, and $\mathcal{AD}^{\varphi}$ are presented in Table 1 for each hearing aid separately and combined. Individual data points for each subject and hearing instrument are displayed in Figure 9. Data for each hearing aid for the noise source at 180° (top panel) and θ[135/225] (bottom panel) are presented as filled (Oticon) and open (Phonak) symbols. Acoustic ($\mathcal{AD}^{\varphi}$ and $\mathcal{AD}_s^{\varphi}$) and behavioral directivity (HINT) are significantly correlated for the noise source at 180° (r = 0.52 for 180° & 0.34 for

TABLE 1. Pearson's correlation coefficients for behavioral directivity, as measured by HINT, and acoustic directivity ($\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$), as measured using real ear techniques

	Oticon	Phonak	Combined
$\mathscr{AD}^{\varphi}$			
180°	−0.11	0.47*	0.52*
θ[135/225]	−0.18	−0.12	−0.14
$\mathscr{AD}_s^{\varphi}$			
180°	−0.06	0.46*	0.34*
θ[135/225]	−0.24	0.20	−0.12

* *Significant correlation ($p < 0.05$)*
HINT: Hearing in Noise Test.

θ[135/225]) when data are collapsed across hearing aids. Note that the correlation is much higher for the Phonak instrument when the noise source is at 180° consistent with the polar pattern of the hearing instruments. The acoustic ($\mathscr{AD}^{\varphi}$) and behavioral (HINT) measures of directivity are negatively correlated in some cases for the noise source at θ[135/225] with the magnitude of negative correlation being higher for the Oticon instrument. Although none of these correlations are significant, these results are in contradiction with the results from the group data as the Oticon instrument is designed to be most directional for noise sources at θ[135/225].

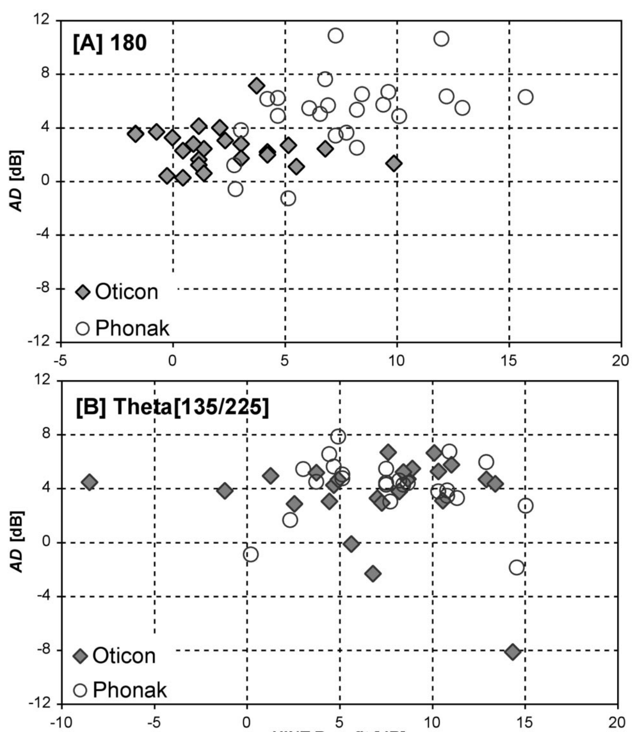

Figure 9. Comparison of directional benefit as measured by HINT and acoustic directivity ($\mathscr{AD}^{\varphi}$) as measured using real ear techniques (equation 2) in all subjects. Results for different hearing aids are presented as different symbols, with the filled and open symbols representing data the Oticon and Phonak instruments, respectively. Data for the two noise sources are presented in different panels (180°, Panel A; θ[135/225], Panel B). Note that these data represent estimates of acoustic directivity made by computing the difference between FBR measurements in omni-directional and directional modes.

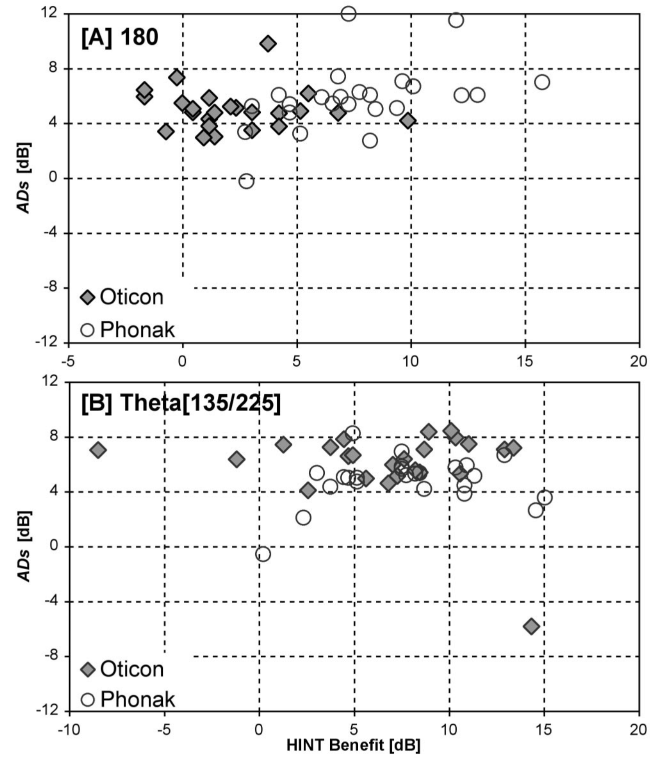

Figure 10. Comparison between directional benefit as measured by HINT and acoustic directivity ($\mathscr{AD}_s^{\varphi}$) as measured using real-ear techniques (equation 3) in all subjects. The format of the figure is identical to that of Figure 9.

In similar fashion, the results of the correlational analysis between behavioral directivity, as measured by HINT, and the simplified measure of acoustic directivity, $\mathscr{AD}_s^{\varphi}$, are presented in Table 1 and Figure 10. Only two of the correlations are significant for the noise source at 180° in this case. Consistent with the $\mathscr{AD}^{\varphi}$ data, correlation is strongest for the Phonak instrument when the noise source is at 180°. The correlation coefficients for the Phonak instrument are positive for both noise sources while those for the Oticon instrument are negative.

DISCUSSION

Attempting to determine predictability of behavioral directional benefit from a conveniently-obtained acoustic benchmark, we measured and compared HINT and REAR data in a fairly homogenous group of 24 hearing-impaired individuals. Our motivation was to arrive at a practical clinical protocol that would allow prediction of real world benefit for directional hearing aids—individualized to the patient and his or her hearing aid(s). First, however, we make a few remarks about the HINT and REAR data in isolation before discussing the correlation between the two.

HINT

The magnitude of directional benefit reported here is in general agreement with previously reported estimates made under comparable conditions (Agnew & Block, 1997; Valente et al., 1995; Voss, 1997). These data reinforce the relationship between directional benefit and omnidirectional performance observed in previous reports (Ricketts & Dhar, 1999). The Phonak instrument appears to provide greater directional benefit in these data (Fig. 5) for the noise source at $\theta[135/225]$. However, this is a direct consequence of omnidirectional performance being worse for this hearing instrument at this angle (Fig. 3). Thus, directional benefit in isolation appears to be a meaningless metric and should always be evaluated with reference to omnidirectional performance. Finally, the directional performance of the hearing aids appears to be in agreement with their published polar patterns, the Oticon and Phonak instruments performing better at 0° and $\theta[135/225]$, respectively. This is an important observation supporting the case for predictability of behavioral benefit from acoustic measures and will be discussed in detail later.

Acoustic Directivity

Most, if not all, established indices of acoustic directivity (e.g., DI, FBR, polar plot, etc.) measure the differential sensitivity of a hearing aid for signals from the front and back. A comparison of omnidirectional and directional performance is not achieved in any of these measures. $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$, as derived here, achieve this goal, thereby allowing direct comparison to behavioral measures, like the HINT, for which a comparison between omnidirectional and directional modes is made. The novelty of the acoustic measures employed here make it difficult to compare our results with those published previously. However, our results are in close agreement with previously published FBR data (Agnew & Block, 1997).

A comparison of Figures 6 and 7 reveals a linear relationship between $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$, with $\mathscr{AD}_s^{\varphi}$ always being greater in magnitude than $\mathscr{AD}^{\varphi}$ by a constant. This constant difference between $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ turns out to be *FC* as is theoretically predicted from Equations 2 and 3. Thus, $\mathscr{AD}_s^{\varphi}$ represents the global change in a hearing aids response when switched between omnidirectional and directional modes. $\mathscr{AD}^{\varphi}$, on the other hand, represents a portion of this overall change attributable solely to the directionality of the hearing aid.

The relationship between our measures of acoustic directivity and the location of the noise sources appear to be in agreement with published polar plots of the hearing instruments in question. While this, along with a similar observation made for HINT data, appear to support predictability of behavioral benefit from acoustic measures, we investigate this issue in greater detail next. A related question of interest is the comparative performance of $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ in predicting behavioral benefit.

Predictability

Moderate statistically significant correlations between HINT results and $\mathscr{AD}^{\varphi}$ or $\mathscr{AD}_s^{\varphi}$ were observed for the noise source at 180° when data were collapsed across hearing aids (Table 1). The statistically significant correlation between $\mathscr{AD}^{\varphi}$ or $\mathscr{AD}_s^{\varphi}$ and HINT measures are encouraging for the predictability of behavioral benefit from acoustic measures.

The group data for the Oticon instrument appear to suggest an agreement between behavioral and acoustic measures of directional benefit (Figs. 5 and 6). However, individual data (Table 1 and Fig. 9) appear to contradict this observation. While we are unable to fully explain this discrepancy, some observations can be made to that end. There appears to be one outlier in the bottom panels of Figures 9 and 10 with $\mathscr{AD}^{\varphi}$ or $\mathscr{AD}_s^{\varphi}$ scores lower than -4. Elimination of this data point from the correlational analyses reduces the magnitude of negative correlation considerably for both $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ bringing them close to "chance." In addition, examination of Figures 9 and 10 reveals a greater range of HINT benefit (abscissa) as compared with the range of acoustic benefit (ordinate), suggestive of greater variability in the amount of behavioral benefit for a given amount of acoustic directionality. This in turn points to factors, perhaps extra-acoustic, that might play a central role in determining the amount of behavioral benefit to a user from a given directional instrument.

Missing Links

While our results demonstrate promise in the use of acoustic measures to predict directional benefit in the real world, several complicating issues become evident after a thorough examination of the data. Why, for example, do these apparently related measures not exhibit stronger correlation irrespective of noise azimuth and hearing instrument? The answer might be in more selective use of the acoustical data or in identification of extra-acoustic factors not related to the performance of the hearing aid.

We collapsed the real-ear measures across frequency to yield a single value for each measure. This might have adversely affected the correlation between acoustic and behavioral measures. Given the frequency composition of speech, and frequency-specific directional effects, as well as frequency-specific hearing loss and hearing aid gain, it might be more appropriate to use a weighting factor (such as SII or Articulation Index) on the acoustical data. Alternately, perhaps REAR values for octave bands centered at frequencies (*f*) of 500, 1000, 2000, and 4000 Hz could be used to compute band-specific values $\mathscr{AD}_f^{\varphi}$, $\mathscr{AD}_{sf}^{\varphi}$, and FC_f.

Behavioral measures of directional benefit, when measured using the HINT, do not account for either the hearing loss of the hearing aid user or the gain settings of the hearing aid. A combination of the hearing loss and the hearing-aid fit could render the noise at 65 dBA inaudible at certain frequencies for a given person even in the omnidirectional mode. When switching the hearing aid to the directional mode, behavioral directional benefit in this case would be minimal, the amount of acoustic directivity notwithstanding. Thus, the hearing loss and the gain-frequency settings of the hearing aid must be incorporated in the computation to better account for the relationship between acoustical and behavioral measures of directivity.

To account for all the above factors (individual hearing loss, particular gain settings, etc.) we computed SII (ANSI S3.5, 1997) values for omnidirectional and directional conditions for each subject and hearing aid. Individual hearing losses along with third octave band levels for the HINT signal and noise were used for this calculation. The HINT signal and noise levels were further transposed using the REAR values for that condition. Specifically, the HINT signal level was modified using the REAR data from 0°, while the HINT noise levels were modified using the REAR values from either 180° or θ[135/225]. Thus, the SII values obtained incorporated individual hearing loss data and specific gain settings for individual hearing aid conditions. SII values for each subject and aided listening condition were then compared with the corresponding HINT thresholds obtained for omnidirectional and directional conditions. No systematic relationship was observed between the SII values and HINT thresholds in this analysis. These results suggest the possible role of extra-acoustic (e.g., physiological, psychological, and environmental) factors in the determination of behavioral benefit. It should be noted however, that the acoustic measures used here to calculate the SII values were not ideally suited for that purpose as we did not plan the experiment with the express goal of calculating SII values for omnidirectional and directional conditions. A more thorough examination of this issue needs to be performed where REAR measures are made with stimuli similar to those used for the HINT.

Study Limitations

The current study sought to determine associations between the immediate acoustic and perceptual benefits for two hearing instruments. It could be argued that the perceptual benefits from a directional hearing aid could change with prolonged usage. Longitudinal measures of perceptual performance were beyond the scope of this study, but remain an interesting issue.

The results reported here were obtained from one ear of each subject. However, most if not all of the subjects would be candidates for binaural amplification. While the HINT is well suited for measurement of binaural performance, real ear results from individual ears would have to be transformed into a binaural score for correlation with the binaural HINT score. Further work is needed to arrive at a suitable and reliable transform before binaural measures of acoustic directivity can be compared with behavioral measures. It can be argued, however, that in case of asymmetrical hearing losses, the two ears will have different SNR values, and binaural performance will be dominated by the ear with better SNR. On the other hand, in case of symmetrical hearing losses, where the SNR is similar between the ears, an increase in performance might be observed for binaural tasks. However, this enhancement of performance is expected to be similar for omnidirectional and directional conditions.

Finally, directional benefit reported here, both perceptual and acoustic, likely represents a combination of several factors and not just a measure of the acoustic directionality of the hearing aid. Specifically, frequency response and compression can contribute to the observed performance with any given hearing aid. For example, the performance of the hearing aids could be very different from that reported here if the user encountered signal levels different from those used in this study. The hearing aids were programmed using the manufacturers' recommended gain settings and similar levels were used for the HINT and real ear measures to simulate real world performance of each hearing aid to the extent possible. While careful design of parameters could allow parsing of directional benefit from all other factors, such a measure may not be related to the real world benefit available to the user from a particular hearing aid.

Measuring $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$

Our results show initial promise of predictability of behavioral benefit from conveniently measured acoustic directivity. The acoustic measures reported here departed from conventional measures of directivity in their correspondence to benefit, as opposed to performance. $\mathscr{AD}^{\varphi}$, which is a purer measure of directivity, exhibits better predictability of behavioral benefit. However, $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ were found to be significantly correlated for noise sources at 0° and θ[135/225], suggesting interchangeability between the two measures. Both $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ can be measured using standard clinical real-ear equipment with one speaker. Initially, the real-ear instrumentation should be set up to measure REAR from 0°. REAR values should be measured in omnidirectional and directional modes in this test configuration. Now, the test configuration should be changed to enable measurement from the "noise angle" (180° or θ[135/225] here). This can be done by repositioning either the speaker or the user. In either case, utmost care should be taken to ensure that neither the distance between the hearing aid and the speaker nor the elevation of the speaker changes. Another set of REAR measures should be obtained from this azimuth in omni- and directional modes. This will result in a total of four REAR measurements. These values can then be plugged into Equation 2 to obtain $\mathscr{AD}^{\varphi}$. In fact, the insertion-gain mode of the real-ear equipment can be used judiciously to generate $\mathscr{AD}^{\varphi}$ and $\mathscr{AD}_s^{\varphi}$ by substituting various aided measures for unaided measures (REUR) in this test mode. Thus, the REAR measures for the omnidirectional and directional conditions could be saved as the "unaided" and "aided" curves. The instrument would then automatically calculate the difference between them. While we present details of both calculations here, the reader should note that their clinical validity needs to be evaluated further before adoption as regular clinical protocol.

CONCLUSION

The main findings of this study can be summarized as follows. First, acoustic measures of directional benefit show initial promise of being able to predict real world benefit. Second, changes in frequency response associated with a switch between omnidirectional and directional modes do not appear to aide speech perception in noise. Third, individuals appear to gain different amounts of behavioral benefit from a limited amount of acoustic advantage provided by a directional hearing aid, pointing towards the role of extra-acoustic factors in determining real world benefit from directional hearing aids. Finally, further parsing out of these extra-acoustic factors along with differential weighting of frequency and indices like the Articulation Index or SII should be examined in the future.

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